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REMOVING THE COSMOLOGICAL BOUND ON THE AXION SCALE

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Abstract

The current cosmological bound on the invisible axion scale may be avoided in the class of theories in which the gauge coupling constant is determined through the expectation value of some scalar field (e.g. moduli in supergravity and string theories). This leads to the cosmological scenario different from that of the standard invisible axion, since the initial values of the fields are usually far away from their true minima, allowing for the color group becoming strong in the very early universe and fixing the axion field to its minimum. The effect disappears as soon as scalar field adjusts to its present value, but the above is enough to ensure that the deviation of the axion expectation value from the minimum is negligible at the moment of the QCD phase transition and thus to eliminate the troublesome coherent oscillations. This may imply that the standard axion window does not necessarily hold in generic supergravity theories. The above observation may open a natural possibility for the existence of the axion resulting from the GUT or R-symmetry breaking.

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1 Introduction

The Peccei-Quinn (PQ) mechanism [1] is a commonly accepted solution to the strong CP problem. This mechanism is based on the concept of the spontaneously broken anomalous chiral $U(1)_{PQ}$ symmetry, with a subsequent light pseudogoldstone boson - axion. Phenomenological and astrophysical constrains [2] suggest to attribute the breaking of $U(1)_{PQ}$ to some $SU(2) \otimes U(1)$-singlet Higgs with a large ($f_a > 10^9 GeV$ or so) vacuum expectation value (VEV) and therefore, to make axion invisible[3]. Furthermore, as is well known[4], the cosmological considerations give the upper bound as well

$$f_a < 10^{12} GeV \tag{1}$$

and one is left with a narrow window.

Clearly, it is extremely important to know if one can avoid (and at what price) the upper bound on the axion scale.

First of all, this would give a natural possibility to implement Peccei-Quinn mechanism in GUTs (without introducing unmotivated intermediate scales).

Secondly, this would solve the cosmological problem of R-axion in generic supersymmetric and supergravity theories[5], even if R-symmetry is exact apart of anomaly. More excitingly, this could give a possibility to use R-symmetry as $U(1)_{PQ}$.

Most importantly perhaps, we want to understand how model independent the cosmological bound is. In the present paper we will argue that this bound is model dependent and in a large class of theories may be absent. In

particular this are the theories in which the strong gauge coupling constant is determined by an expectation value of a scalar field, e.g. generic supergravity and superstring theories.

2 Cosmological Constraint

Let us first briefly recall the origin of the constraint. In the invisible axion scenario[3], the breaking of the Peccei-Quinn symmetry is induced by the $SU(3) \otimes SU(2) \otimes U(1)$-singlet Higgs field ϕ with a 'Mexican hat' potential

$$V = \lambda(|\phi|^2 - f_a^2)^2 \tag{2}$$

At the bottom of this potential the complex field can be represented as $\phi = f_a e^{i\frac{a}{f_a}}$, where a is the angular goldstone mode - axion, parameterizing the flat minimum. QCD instanton effects lift the vacuum degeneracy and induce effective potential for a

$$V_a = \Lambda_{QCD}^4 (1 - cos\frac{aN}{f_a}) \tag{3}$$

Here N stands for the non-anomalous Z_N subgroup and may lead to the domain wall problem [6] if the Peccei-Quinn phase transition (if it happens *at all* [7]) takes place after inflation. In our scenario this never happens (essential point is that PQ field is nonzero and large during and after inflation) and all topological defects are inflated away. So below we will simply assume $N = 1$.

In the context of the standard big bang scenario it is usually assumed that the phase transition with $U(1)_{PQ}$-symmetry breaking occurs when the

universe cools below the temperature $T_c \sim f_a$. Certainly, this is so for the case of a single Higgs field, but need not be true in general. First, as it was shown recently [7], even the minimal invisible axion model can exhibit symmetry *nonrestoration*[8] at high T. Secondly, in the inflationary scenarios the VEV of ϕ can be strongly shifted during inflation due to the coupling with the inflaton field and therefore be nonzero from the 'very beginning'. (In general, this is true for any Higgs field, so that even $SU(2) \otimes U(1)$ can be strongly broken during inflation). One way or another, in the standard case the crucial assumption is that from the very moment of the Peccei-Quinn phase transition and all the way down to the temperatures $\sim \Lambda_{QCD}$, the bottom of the potential (2) is exactly flat and there is no prefered value of a during this period ((3) vanishes). Consequently, at the moment of the QCD phase transition, when the instanton effects lift degeneracy, a rolls to the minimum and starts coherent oscillations about it with large initial amplitude $A \sim f_a$. The energy density stored in such oscillation is

$$E_a \sim m_a^2 A^2 \tag{4}$$

where $m_a \sim \frac{\Lambda_{QCD}^2}{f_a}$ is the axion mass. Of course, the switch-on of the axion mass is not sudden and this fact somewhat reduces the constraint. More detailed analysis [4] shows that universe had to be overclosed by above coherent oscillations unless the VEV of ϕ is restricted by (1).

Clearly, this upper bound on f_a can be avoided, if there have been some mechanism guaranteeing that at the moment of QCD phase transition a starts oscillations with much smaller initial value $A << f_a$. This can be the case if in the early universe one assumes a period during which vacuum

degeneracy was strongly lifted, with axion having a mass of order the Hubble constant (H), so that a could rapidly settle in to the minimum $a = 0$. Of course, below certain temperature $T_R >> \Lambda_{QCD}$ this effect had to disappear and bottom of the potential had to become again flat until the 'usual' QCD phase transition, but the dramatic consequence of such a period would be that at T_R axion appears to sit at its zero temperature minimum. Below T_R the thermal fluctuations will try to drive a away from zero, but resulting deviation for the moment of QCD transition will be very small if T_R is small enough. In the next section we consider theories exhibiting such a cosmological behavior.

3 Scenario with inflation

The theory with above nonstandard cosmological history can be one in which the gauge coupling constant is fixed by VEV(s) of some scalar field(s). For example, such a situation is common in generic supergravity and superstring theories in which the gauge coupling constants is determined through the following type term in the Lagrangian [9]

$$f(\frac{Z}{M_p})F_{\mu\nu}F^{\mu\nu} \tag{5}$$

where $F_{\mu\nu}$ is gauge field tensor, f is some (real) function of the field Z and M_p is the Planck scale. In the superstring theories Z is a dilaton field (S) and function f has the form (in Planck scale units) $f(S) = ReS + thresold\ corrections$. In generic supergravity theories $f(Z)$ may have whatever form, provided that its low temperature expectation value sets the

correct gauge coupling constant in the true vacuum with zero energy. Certainly, there is no reason to assume that the value f had to be the same in the early universe, since the scalar VEVs, in general, are far away (by $\Delta Z \sim M_p$) from their low temperature minimum. This is the case both because of thermal and quantum fluctuations and also because the minimum itself becomes displaced from the present place. In particular, this fact is precisely the origin of the cosmological moduli problem [10], and it is interesting how the assumption that creates a problem in one case, may provide a solution in another. For us the most important consequence of this fact is that it can allow for the QCD becoming strong during some period in the early history and giving to the axion the mass $\sim$ Hubble constant at that time.

Most easily (but not only) this may happen in the inflationary scenarios[11], since both Z and ϕ in general are getting large displacement due to interaction with the inflaton field. For example, if Z is a string moduli, in general it will get large $\sim M_P$ shift due to the fact that normally inflation generates a curvature $\sim H$ to its potential [12], and because at present potential is very flat (and VEV is $\sim M_p$), the resulting shift is very large. In addition it is also possible that Z-field, that fixes gauge coupling, itself can be an inflaton field.

In general VEV of the PQ field also will be displaced from its true value f_a. If selfcoupling of ϕ is not very small, the mass of the radial mode at the bottom of the potential is $\sim f_a$. Since in the present context we assume f_a being non-standardly large (GUT scale or even M_p), significant displacement is not expected, unless ϕ is directly coupled to the inflaton (or unless $H > f_a$,

which is unlikely to be the case). Of course, it is perfectly possible that either selfcoupling is very small, or PQ field has unsuppressed coupling with inflaton. In such a case the displacement can be large. So we assume that the natural nonzero VEV of ϕ in inflationary epoch is $\sim f_a$ (or even larger).

Now what about the early history of the electroweak Higgs sector? Again, this is very model-dependent situation. Behavior of the electroweak Higgs doublets in the inflationary era is determined by several factors and in particular by their coupling with other (GUT) Higgses and with inflaton. However, even in the minimal cases their displacement from the normal (almost zero) VEVs can be large. For example, in the minimal supersymmetric standard, model with a single pair of the Higgs doublets H and $\bar{H}$, the scalar potential is almost flat in the direction $|H| = |\bar{H}| = arbitrary$ and $all\ other\ fields = 0$. (There are other flat directions which involve squarks and slepton VEVs, but they are not of our interest here). In the supersymmetric limit this flat direction is shut down by the supersymmetric mass term $\mu H\bar{H}$ (μ-term) in the superpotential, which generates small weak scale curvature ($\sim 100GeV$). After SUSY breaking there is an additional contribution of the comparable strength from the soft terms. Therefore, effective curvature in $SU(2) \otimes U(1) - breaking$ direction is very small and resulting shift during inflation can be large. In the supergravity case, even in the absence of the direct coupling with inflaton, this direction will get universal gravity transfer contribution $\sim H$ to the curvature, very much like moduli fields. For the canonical Kahler potential this contribution is positive, but can be negative for the more general form. However, unlike moduli, Higgs doublets are gauge nonsinglets and have renormalizable couplings with matter fields and they can (and will) get

negative corrections to the mass from other (radiative) sources as well [13]. So the outcome is that, in general, there is no particular reason for the Higgs doublet VEVs to vanish during inflation and their typical magnitude can be at least $\sim H$.

One way or another, in general we expect that QCD may naturally become strong for some period (during inflation). Assuming that at that time $m_a \sim H$, a will settle at $a = 0$ and stay there before QCD instantons will be switched-off. Clearly, this effect has to disappear after inflation ends (or may even before) and all the VEVs $(\phi, Z, H, \bar{H})$ adjust to their normal values. Below this point universe is reheated to some temperature T_R and the hot bing bang starts. Influence of thermal effects on the values ϕ and $f(\frac{z}{M_p})$ are negligible provided $T_R << f_a, M_p$ and so we assume that in the interval of temperatures $T_R > T > \Lambda_{QCD}$ the QCD instantons are switched-off and $m_a = 0$, as it is assumed in the standard scenarios. The important outcome in our case is that at $T \sim T_R$ axion field is fixed at $a = 0$. But now, the thermal fluctuations will try to drive a away from zero. Since the bottom of the potential is exactly flat, journey along it can be considered as a random walk with a step $\Delta a \sim T$ per Hubble time. This means that during the temperature interval $T_R - \Lambda_{QCD}$ it can cause (at best) the deviation $A \sim T_R$ of the axion field from the minimum. Thus the energy stored in the coherent oscillations becomes

$$E_a \sim m_a^2 T_R^2 \sim \Lambda_{QCD}^4 \frac{T_R^2}{f_a^2} \tag{6}$$

We see that this energy is suppressed with respect to the standard case by an extra factor $\sim \frac{T_R^2}{f_a^2}$. No definite information exists about the reheat tem-

perature T_R at present. For example, the solution of the gravitino problem requires $T_R < 10^9$[14]. In general, if the electroweak baryogenesis [15] can be trusted, T_R can be as small as electroweak scale. This means that for the GUT scale axion the oscillation energy may be suppressed by a factor of order 10^{-28} with respect to the usual case! For our purposes such a small reheat temperature is not needed and it is perfectly enough that T_R is few orders of magnitude below f_a. This fact avoids cosmological bound (1) on the axion scale and allows it to be as large as the GUT or Planck scale without any trouble.

4 Quantum fluctuations during inflation

In the above analysis, for simplicity, we were assuming that the epoch of the superstrong QCD ends together with inflation. Of course, in a more general case this may happen while inflation is still in progress. Since axion potential becomes flat, the quantum de Sitter fluctuations, presented during inflation, will drive a away from zero very much like thermal effects in the previous section. Now the step is $\Delta a \sim H$ during the Hubble time H^{-1} and resulting dispersion after N Hubble times is $\sim H\sqrt{N}$[16]. Anisotropy of the microwave background radiation induced by the fluctuations in the axion field at the late stages of inflation may require small (large) values of H (f_a) at that time [17]. After reheating, the contribution of the thermal fluctuations to the amplitude is similar as in our previous discussions and is of order T_R. Of course, the precise values H and T_R are model-dependent and can not be studied here, but the message is that in any case coherent oscillations can

be strongly suppressed, if both T_R and H (during inflation) are somewhat smaller f_a.

5 Constraints from axionic cosmic strings and domain walls

Another possible constraint[18] on the Peccei-Quinn scale comes from the decay of the global axionic strings [19] and the models with $N > 1$ suffer from the domain wall problem[6]. It should be clear that no such constraint can be applied in our case, since essential point is that both f_a and m_a are nonzero and large during inflation. This simply means that all existing topological structures such as string-wall systems[19] and walls without strings (pure strings can not exist due to nonzero m_a) will be inflated away. Production of the new defects by quantum de Sitter fluctuations is exponentially suppressed by the factors $\sim \frac{f_a^2}{H^2}$ and $\sim \frac{m_a f_a^2}{H^3}$ for the string and wall cases respectively [20].

6 Anthropic principle

Number of authors [21] have pointed out that the cosmological constraint (1) can be avoided by the arguments based on the anthropic principle. According to this arguments we observe universe with $A << f_a$, because inflation has produced domains filled with all possible values of the axion field a (A), but in the domains with $A \sim f_a$ life is impossible. Therefore, the only place we have a chance to see ourselves is a domain with small enough A.

In our scenario there is no need in anthropic principle, since now, all the

domains produced by inflation have $A << f_a$ due to the fact that m_a was large in that epoch.

7 Summary and outlook

We have argued that there is a large class of theories in which current cosmological constraints on the axion scale may be naturally avoided. In particular, this are theories in which a VEV of a scalar field can determine the strength of the gauge coupling, as it happens in generic supergravity and superstring theories. In such an approach the gauge constant becomes a dynamical variable and is driven by the evolution of the scalar field. The crucial point is that in the early universe VEVs are far away from their true minima, allowing for QCD to become strong at some high scale and fixing axion field to minimum. The deviation from $a = 0$ (induced by thermal or quantum fluctuations) at the moment of the ordinary QCD phase transition is determined by the reheating temperature and can be naturally small.

This effect opens a possibility for the existence of a GUT (or M_p) scale axion and for avoiding problems related with the R-axion in supersymmetric theories.

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